New LCA Theses

Environmental Life Cycle Assessment in Microelectronics Packaging

Thesis for the degree of doctor of philosophy ISBN 91-7291-607-9, ISSN 0346-718X

Anders S.G Andræ

Department of Microtechnology and Nanoscience, Chalmers University of Technology, 412 96 Göteborg, Sweden (a.andrae@aist.go.jp)

DOI: http://dx.doi.org/10.1065/lca2006.03.004

An increased understanding of the application of environmental Life-Cycle Assessment (LCA) methodologies in the microelectronics packaging area should help in developing environmentally sound product systems.

The aim of the present thesis is to increase the knowledge of using LCA tools, methods and models, in application to current and new microelectronic products. A subgoal is to establish a better understanding of how to collect data to be used in a Life-Cycle Inventory (LCI) and environmentally assess the importance of the upstream processes. The objective has been to explore how variants of LCA could be used in microelectronics applications, and how the LCA software *EcoLab* and available data were utilised to analyse environmental loads.

Different case studies were performed on (i) microelectronic products, (ii) substrate and soldering materials, and (iii) plating and soldering processes. The main emphasis has been on the upstream processes. Analysis of the results shows that the input data needed for environmental assessment of electronics applications comes from many different sources. An LCI data collection model applicable to most electronic products helps in quantifying upstream processes. This is explained for a digital telephone. The global shift from Sn-Pb to Pb-free solder paste was modelled using attributional LCA and consequential LCA. It was found that the attributional and consequential methodologies yield complimentary knowledge about the environmental consequences of the shift.

In this thesis, uncertainty estimation in LCI using Monte Carlo simulation was also investigated. The approach was applicable to small, one-parameter, cradle-to-gate systems. There are strong indications that electrochemical pattern replication is more CO_2 efficient than conventional photolithography, and that glass fibre enforced liquid crystalline polymers are more CO_2 efficient than the corresponding brominated epoxy (FR4), polytetrafluoroethylene (Teflon®) and ceramic/glass tape.

In addition to this, the effect of system expansion of manufacturing processes of the new packaging concept System-In-a-Package was addressed. This expansion of the upstream product system changes the relative environmental importance of manufacturing processes.

Overall, environmental LCA are applicable to microelectronics packaging, but the assessments are hampered by the lack of readily available input LCI data.

Keywords: Attributional environmental life-cycle assessment; consequential life-cycle assessment; data collection; environmental life-cycle inventory; microelectronics packaging; microelectronic products; System-In-a-Package; uncertainty analysis; upstream processes

List of Appended Papers

The work presented in this thesis is based on the following publications, referred to by their Roman numerals. The papers are appended at the end of the thesis.

I. Andræ ASG, Östermark U, Liu J (2000): Life Cycle Assessment of a Telecommunications Exchange. Journal of Electronics Manufacturing 10 (3) 147–160

II. Andræ ASG, Andersson DR, Liu J (2005): Significance of Intermediate Production Processes in Life Cycle Assessment of Electronic Products Assessed Using a Generic Compact Model. Journal of Cleaner Production 13 (13–14) 1269–1279

III. Ekvall T, Andræ ASG (2005): Attributional and Consequential Environmental Assessment of the Shift to Lead–Free Solders. Int J LCA, Accepted, OnlineFirst <DOI: http://dx.doi.org/10.1065/lca2005.05.208>

IV. Andræ ASG, Andersson DR, Ramberg C, Bengtsson B, Liu J (2005): Application of Simplified Methods for Partial Environmental Assessment of Microelectronics Soldering Materials and Processes in Small and Medium Sized Enterprises. Gate to Environmental and Health Science (Internet-Journal Gate to EHS). <DOI: http://dx.doi.org/10.1065/ehs2005.05.001>

V. Andræ ASG, Möller P, Anderson J, Liu J (2004): Uncertainty Estimation by Monte Carlo Simulation Applied to Life Cycle Inventory of Cordless Phones and Microscale Metallization Processes. IEEE Transactions on Electronics Packaging Manufacturing 27 (4) 233–245

VI. Chen L, Andræ ASG, Zou G, Liu J (2004): Characterization of Substrate Materials for System-in-a-Package Applications. Journal of Electronics Packaging 126 (2) 195–201

VII. Andræ ASG, Zou G, Liu J (2004): LCA of Electronic Products – An Environmental Assessment of Gallium Arsenide Monolithic Microwave Integrated Circuit System-In-a-Package (SIP) Switch Product. Int J LCA 9 (1) 45–52

VIII. Andræ ASG, Chen L, Schischke K, Hagelueken M, Liu J (2004): Environmental Assessment of Embedded Chip Manufacturing Technology. In: Proceedings of Electronics Goes Green 2004+, Sept. 6–8, Berlin, Germany, pp 913–918

The thesis includes a thorough introduction and the following papers:

1. Paper I looks at the application of LCA, using the LCA software *EcoLab* in a large microelectronics system, namely a telecommunications private branch exchange. For the first time, LCA was applied to this product and the impact from business travelling was allocated to the total environmental load. It is shown that the hardware production contributes substantially to the life-cycle environmental load. The LCA was carried out at Ericsson Enterprise together with their staff and consultants. The paper is written by Andræ, while Östermark was the main consultant in the project.
2. In Paper II, Andræ developed a life-cycle inventory data collection model in order to quantify the intermediate unit processes portion of the upstream CO_2 emissions released during the manufacturing of a digital telephone. The paper is written by Andræ. Liu took part in the discussions.
3. In Paper III, Andræ used two different LCA models in *EcoLab* to describe the environmental shift from a Sn-Pb solder to a Pb-free paste. The study was carried out in co-operation with Dr. Tomas Ekvall at Div. of Energy Technology, Chalmers. It is shown that the *attributional LCA* model compliments the *consequential LCA* model. Ekvall developed the conceptual models and wrote most of the paper. Andræ had a major role and performed data collection, calculations, and presented results.
4. This paper looks at the application of simplified tools, instead of LCA, for use in small and medium sized enterprises manufacturing microelectronics. It is shown that the Toxic Potential Indicator tool, based on Material Safety Data Sheet, is time efficient as compliment to checklist approaches. However, even the Toxic Potential Indicator needs more input information than is readily found by SMEs. The paper is written by Andræ. Andersson provided contacts with enterprises. Bengtsson and Ramberg developed the checklist.
5. In this paper, Andræ studied the application of uncertainty analysis in life-cycle inventory calculations. The influence of input CO_2 emission uncertainty on output CO_2 emission uncertainty was studied for small product systems; (i) DECT phones compared to GSM phone, phones used in offices and (ii) electrochemical pattern replication compared to conventional photolithography for Cu metallization of Si substrate. Lognormal distributed standard deviations were set to the best estimate values and MATLAB® was used for the simulation. There are strong indications that the electrochemical pattern replication is more electricity efficient than conventional photolithography. Andræ made the modelling and simulations, and wrote the paper. The company ASCOM provided design data on DECT phones. Möller provided expertise on microscale metallization technologies. Anderson took part in discussions about distributions and interpretation of the results.
6. In this paper, Andræ took part in a substrate characterisation study where liquid crystalline polymers were compared to three other materials, FR4, Teflon® and ceramics, for use in SIP. Liu Chen wrote the paper and performed mechanical reliability calculations, Gang Zou investigated electrical performance, and Andræ performed an environmental assessment. For the input inventory parameter, CO_2 emission uncertainty modelling was made in Microsoft Excel® and it is shown that glass fibre enforced LCPs could be an environmentally preferable material compared to FR4, Teflon® and ceramics. Andræ wrote about the environmental assessment part in this paper.
7. In paper VII, Andræ, with Gang Zou, performed an environmental assessment of the manufacturing of a SIP product. The effect of system expansion was investigated using *EcoLab*. Gang Zou manufactured the GaAs monolithic microwave IC based SIP switch in MC2, and Andræ used Zou's material and energy consumption figures, for his calculations. Spin coating and deposition are shown to be important aspects with the system boundaries. The life-cycle inventory data collection model from Paper II worked for the SIP switch. Andræ has written the paper except the part on manufacturing which was written by Zou. Johan Liu has been supervising this work.
8. In this paper, Andræ analysed system expansion of the manufacturing of a Si based System-In-a-Package product manufactured by Liu Chen. Karsten Schischke of Fraunhofer IZM in Berlin provided the Toxic Potential Indicator based Process Toxicity method to identify risks connected to the process steps. Schischke made the ProTox analysis. It is shown that the system expansion changes the relative importance of manufacturing processes. Liu Chen made measurements of the electricity consumptions of the gate-to-gate manufacturing system. Andræ wrote the paper. Johan Liu took part in the discussions.